# 4 Global Overview of Deep-water Exploration and Production

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## Executive Summary

Exploration and production (E&P) in deep water (500–2000 m [1640–6560 ft]) and ultra-deep-water (>2000 m [>6560 ft]) settings have expanded greatly during the past 20 years, to the point at which they are now major components of the petroleum industry's upstream budgets. Most exploration and production activity has concentrated in only three areas of the world: the northern Gulf of Mexico, offshore Brazil, and offshore West Africa, although activity is increasing in several new areas. Globally, deep water remains an immature frontier, with many deep-water sedimentary basins being only lightly explored. Although deep-water discoveries account for less than 5% of the current worldwide oil-equivalent resources, the amount is increasing rapidly. Importantly, these resources are primarily oil; gas exploration is immature, reflecting infrastructure and economic limitations. There have been at least 42 giant fields (>500 million BOE) discovered in deep water.

By year end 2003, approximately 78 billion BOE of total resources had been discovered in deep water from 18 basins on six continents. This total consists of 48 BBO and condensate and 174 TCFG. Deep water contains 85% of the reserves and ultra-deep water has 15%. The immaturity of the play is illustrated by the fact that >50% of the reserves have been discovered since 1995, with 31% being developed and 5% produced. The exploration success ratio, particularly in basins such as the northern Gulf of Mexico and offshore West Africa, has been increasing. Most of these successes are in settings with younger (Cenozoic, mostly Neogene) sandstone reservoirs with direct hydrocarbon indicators (DHIs). However, there is an increasing number of reservoirs without DHIs (generally reservoirs that are slightly older, deeper, and/or with diminished seismic attributes).

Geologic setting and structure are major controls on the occurrence and volumes of hydrocarbons in deep water. Most of the reserves occur in basins with mobile substrates (salt or shale) in confined basins. The sedimentary loading leads to stacking of reservoirs and numerous structural and stratigraphic opportunities for the trapping of petroleum. Most of the traps are combined structural and stratigraphic. In addition, there are numerous migration pathways and source rocks in these types of basins. Adequate seals are commonly present in these clay-dominated, siliciclastic depositional systems.

Deep-water exploration and production, although relatively immature, has considerable potential. Five trends that will drive deep-water development include: 1) continued exploration in established trends; 2) exploration in new basins lacking updip production as well as new trends in unconfined basins, contractional margins, pre-Cenozoic targets, non-deep-water settings, and non-DHI settings; 3) increased focus on gas production; 4) drilling in deeper settings like ultra-deep water; and 5) taking advantage of politically favorable opportunities.

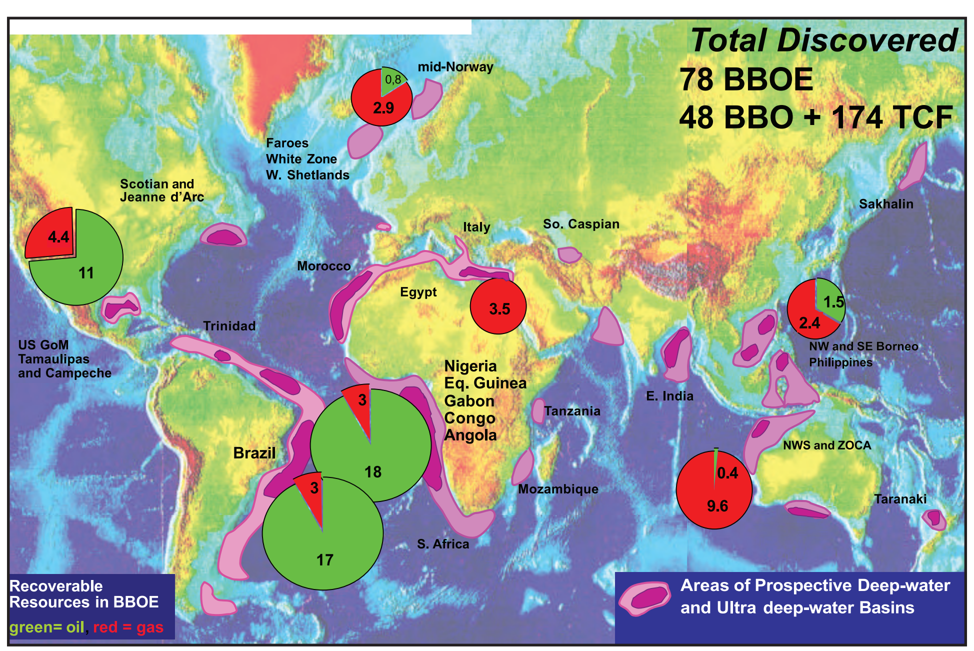


**Figure 1.** Total discovered deep-water (>500 m [>1650 ft]) recoverable resources per region, announced as of November 2003 (BBOE = billion barrels oil equivalents). Major prospective deep- and ultra-deep-water basins are also shown. Green = oil; red = gas. Updated from Weimer and Pettingill (2004). NWS = northwest shelf; ZOCA = zone of cooperation area.

**Table 1.** Resource summary from major producing regions.

| Region | Total deep-water resources | Number of discoveries | Average discovery size* | Largest discovery | | Reservoir age |
|---|---|---|---|---|---|---|
| Campos Basin, Brazil | 15.9 MMBOE | 45 | 385 MMBOE | 3200 MMBOE | Roncador | Cretaceous, Paleogene, Miocene |
| U.S. Gulf of Mexico | 15.5 MMBOE | 160+ | 119 MMBOE | 1000 MMBOE | Thunderhorse | Pleistocene |
| Lower Congo, Angola/ Congo | 10.6 MMBOE | 49 | 216 MMBOE | 975 MMBOE | Dalia | Paleogene, Neocene |
| Niger Delta, Nigeria/Eq. Guinea | 8.6 MMBOE | 34 | 308 MMBOE | 880 MMBOE | Agbami | Neogene |
| Borneo (Mahakam and Baram), Indonesia/Malaysia | 3.9 MMBOE | 20 | <305 MMBOE | 550 MMBOE | Kikeh | Neogene |
| NW Shelf, Australia | 60.1 TCFE | 15 | 4.6 TCFE | 20.0 TCFE | Jansz | Jurassic, Cretaceous |
| Nile Delta, Egypt | 21.0 TCFE | 23 | 0.9 TCFE | 4.0 TCFE | Simian | Neogene |
| mid-Norway (More and Voring) | 15.3 TCFE | 4 | n.m. | 13.9 TCFE | Ormen Lange | Cretaceous, Paleocene |

• published discoveries only
n.m. = not meaningful (only 2 discoveries with resources disclosed)
TCFE = trillion cubic feet equivalent; MMBOE = million barrels oil equivalent; BBOE = billion garrels oil equivalent.

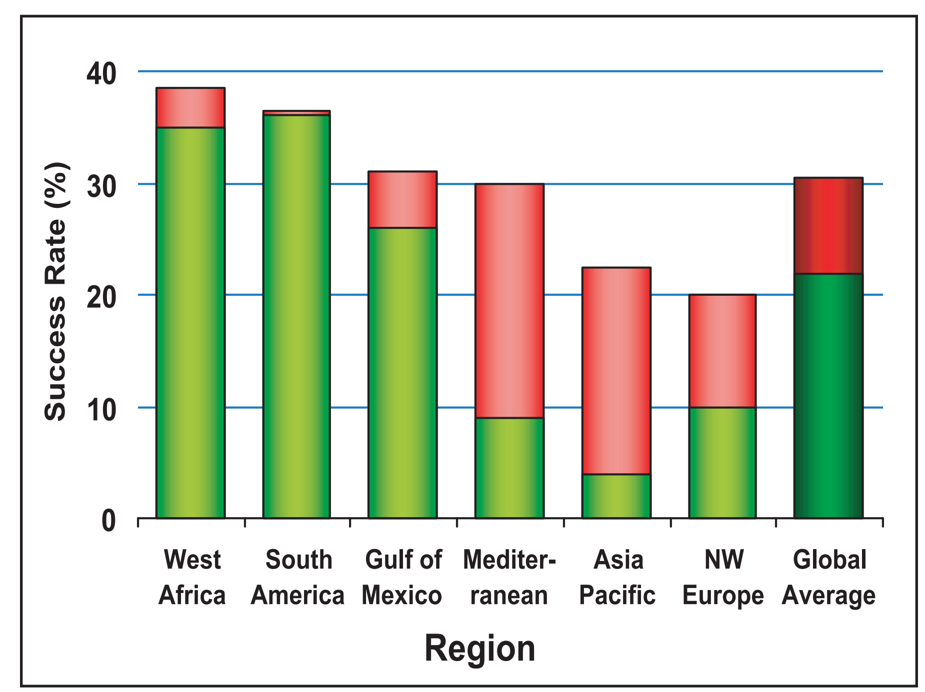


**Figure 2.** Exploration success rates in the six primary deep-water regions of the world and the global average. Green = oil; red = gas. Data from Harper (1997) and Weimer and Pettingill (2004).


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**Table 2.** Giant deep-water discoveries (>500 MMBOE). Several are not fully appraised and are expected to change significantly.

| Basin and Country | Discovery Name | Discovery Year | Status | Recoverable Resources | Water Depth (m) | Resource Reference |
|---|---|---|---|---|---|---|
| Gulf of Mexico, USA | Mars | 1989 | Producing | 486 million bbl oil + 504 bcf | 1014 | IHS, 2003 |
| Gulf of Mexico, USA | Tahiti | 2002 | Discovery | 502 million BOE | 1231 | IHS, 2003 |
| Gulf of Mexico, USA | Thunderhorse | 1999 | Discovery | 1.0 billion BOE | 1963 | IHS, 2003 |
| Campos, Brazil | 1-ESS-121 | 2002 | Discovery | 660 million bbl oil | 1426 | IHS, 2003 |
| Campos, Brazil | Albacora | 1993 | Producing | 872 million bbl oil + 549 bcf | 1000 | IHS, 2003 |
| Campos, Brazil | Barracuda | 1989 | Producing | 807 million bbl oil + 316 bcf | 1160 | IHS, 2003 |
| Campos, Brazil | Marlim | 1985 | Producing | 2.7 billion bbl oil + 1.2 tcf | 853 | IHS, 2003 |
| Campos, Brazil | Marlim Sul | 1987 | Producing | 2.5 billion bbl oil + 1.3 tcf | 1120 | IHS, 2003 |
| Campos, Brazil | Roncador | 1996 | Producing | 2.9 billion bbl oil + 1.75 tcf | 1853 | IHS, 2003 |
| Santos, Brazil | 1-RJS-582 | 2002 | Discovery | 288 million bbl oil + 139 bcf (poss. 300–600 million BOE) | 1493 | IHS, 2003 |
| Santos, Brazil | 1-SPS-35 | 2003 | Discovery | 7.7 tcf | 485 | IHS, 2003 |
| Møre, Norway | Ormen Lange | 1997 | Discovery | 13.2 tcf +138 million bbl cond. | 886 | IHS, 2003 |
| Nile Delta, Egypt | Scarab-Saffron Complex | 1998 | Producing | 4.5 tcf total | 612 | IHS, 2003 |
| Nile Delta, Egypt | Simian | 1999 | Discovery | 2.5–4.0 tcf | 579 | IHS, 2003; Upstream, 2002 |
| Lower Congo, Angola | Dalia | 1997 | Developing | 900 million bbl oil + 450 bcf | 1360 | IHS, 2003 |
| Lower Congo, Angola | Girassol | 1996 | Producing | 725 million bbl oil + 950 bcf | 1365 | IHS, 2003 |
| Lower Congo, Angola | Hungo | 1998 | In development | 700 million bbl oil + 150 bcf | 1202 | IHS, 2003 |
| Lower Congo, Angola | Kissanje | 1998 | In development | 500 million bbl oil + 300 bcf | 1011 | IHS, 2003 |
| Niger Delta, Nigeria | Agbami | 1998 | Discovery | 780 million bbl oil + 576 bcf | 1435 | IHS, 2003 |
| Niger Delta, Nigeria | Akpo | 2000 | Discovery | 590 million bbl oil + 1.2 tcf | 1366 | IHS, 2003 |
| Niger Delta, Nigeria | Bonga | 1995 | Developing | 735 million bbl oil + 451 bcf | 1125 | IHS, 2003 |
| Niger Delta, Nigeria | Bonga Southwest | 2001 | Discovery | 500 million bbl oil + 500 bcf | 1245 | IHS, 2003 |
| Niger Delta, Nigeria | Bosi | 1996 | Discovery | 683 million bbl oil + 2.3 tcf | 1424 | IHS, 2003 |
| Niger Delta, Nigeria | Nnwa-Doro | 1999 | Discovery | 4.4 tcf | 1283 | IHS, 2003 |
| Krishna Godivari, India | Dhirubhai | 2002 | Discovery | 4.8 tcf | 1006 | IHS, 2003 |
| W. Palawan, Philippines | Malampaya-Camago | 1989 | Producing | 3.5 tcf +198 million bbl oil/C | 736 | IHS, 2003 |
| Baram (Sabah), Malaysia | Kikeh | 2002 | Discovery | 530 million bbl oil | 1341 | IHS, 2003 |
| Bonaparte, Australia | Sunrise-Loxton-Sunset | 1975 | Discovery | 7.7 tcf + 299 million bbl cond. | 159 | IHS, 2003 |
| Browse, Australia | Brecknock | 1979 | Discovery | 5.3 tcf +103 million bbl cond. | 543 | IHS, 2003 |
| Carnarvon, Australia | Callirhoe | 2001 | Discovery | 3.5 tcf | 1221 | IHS, 2003 |
| Carnarvon, Australia | Chrysaor | 1995 | Discovery | 2.9 tcf + 75 million bbl cond. | 806 | IHS, 2003 |
| Carnarvon, Australia | Geryon-Orthrus | 1999 | Discovery | 4.0 tcf +1.2 million bbl cond. | 1231 | IHS, 2003 |
| Carnarvon, Australia | Io | 2001 | Discovery | included in Jansz | 1352 | -------- |
| Carnarvon, Australia | Jansz | 2000 | Discovery | 20 tcf + 54 million bbl cond. | 1321 | IHS, 2003 |
| Carnarvon, Australia | Scarborough | 1979 | Discovery | 6.0 tcf | 912 | IHS, 2003 |

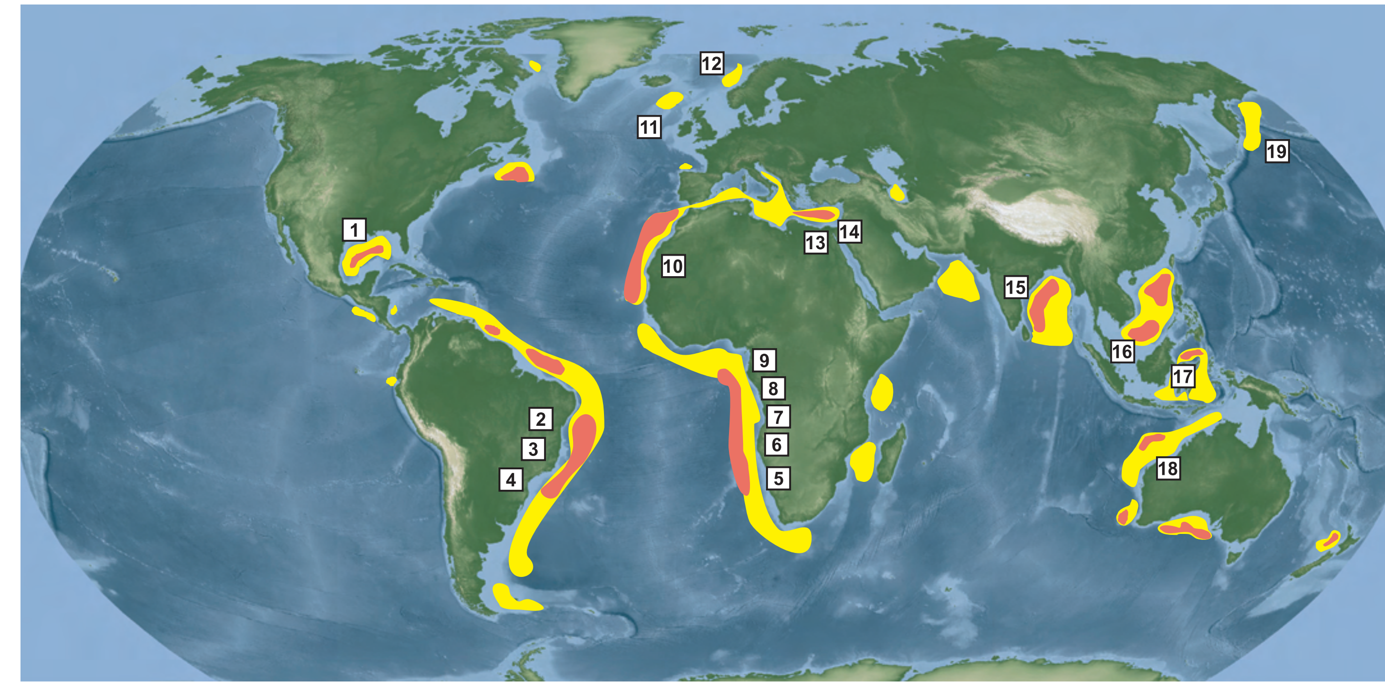
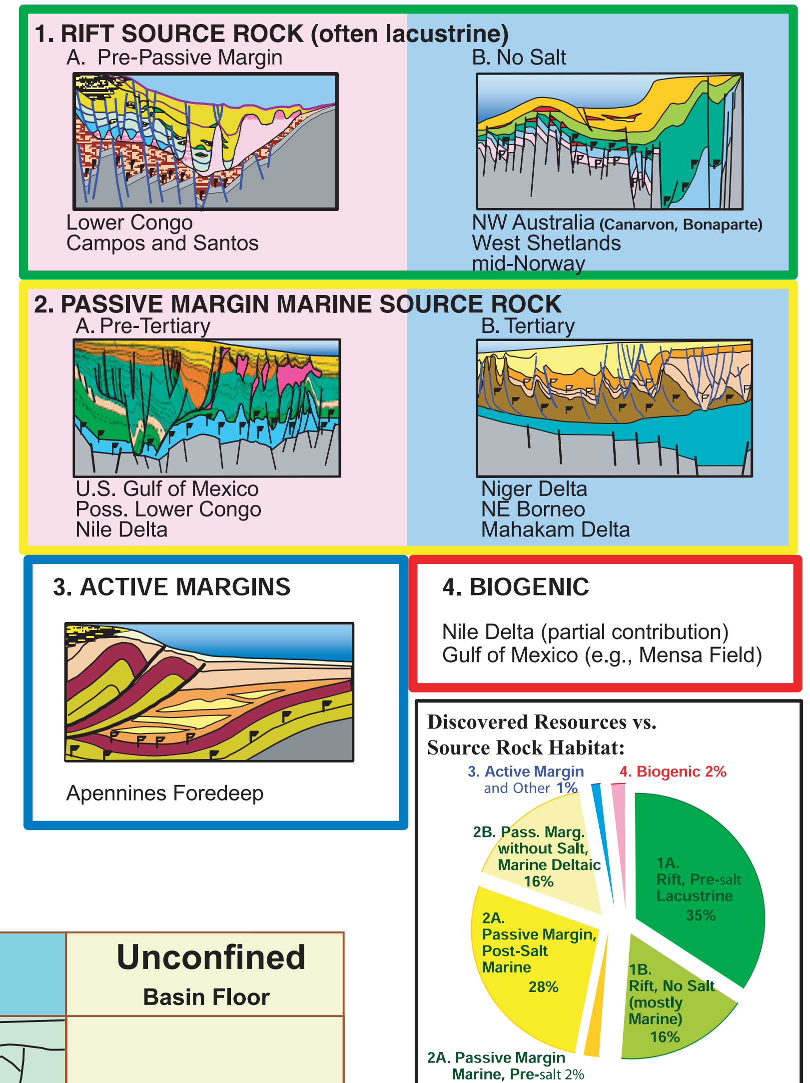



**Figure 3.** Map showing the global distribution of deep-water basins with production and/or announced discoveries: 1) northern Gulf of Mexico, 2) Sergipe-Alagoas, 3) Campos, 4) Santos, 5) Angola, 6) Congo, 7) Gabon, 8) Equatorial Guinea, 9) Niger Delta, 10) Mauritania, 11) offshore Shetlands Islands, U.K., 12) mid-Norway, 13) Nile, 14) Israel, 15) Krishna-Godivari, 16) northwest Borneo (offshore Sabah), 17) eastern Borneo (offshore Mahakam delta), 18) northwest Australia, and 19) Sakhalin Island. Major prospective and ultra-deep-water areas are shown. Yellow = deep-water basins; orange = ultra-deep-water basins.

## Setting, structure, trap style, age, lithology, and source rock

**Figure 4.** Schematic cross sections illustrating the different petroleum systems for deep-water settings. Each section shows the relationship of source rocks with structural styles, stratigraphic fill, and migration pathways. 1. Rift source rocks (often lacustrine) A) with salt deformation: Campos and Santos Basins (Brazil) and Lower Congo Basin (offshore Angola), B) basement blocks: northwest Australia, west of Shetlands, and mid-Norway. 2. Marine source rocks A) early divergent margins: northern Gulf of Mexico, lower Congo and Nile, B) Cenozoic divergent margin: Niger Delta, northwest Borneo. 3. Active margins: Apennine foredeep, Kutei Basin (Mahakam Delta). 4. Biogenic gas: Nile Delta, northern Gulf of Mexico. Inset chart illustrates the relative amount of discovered resources versus source rock. After Pettingill and Weimer (2001).



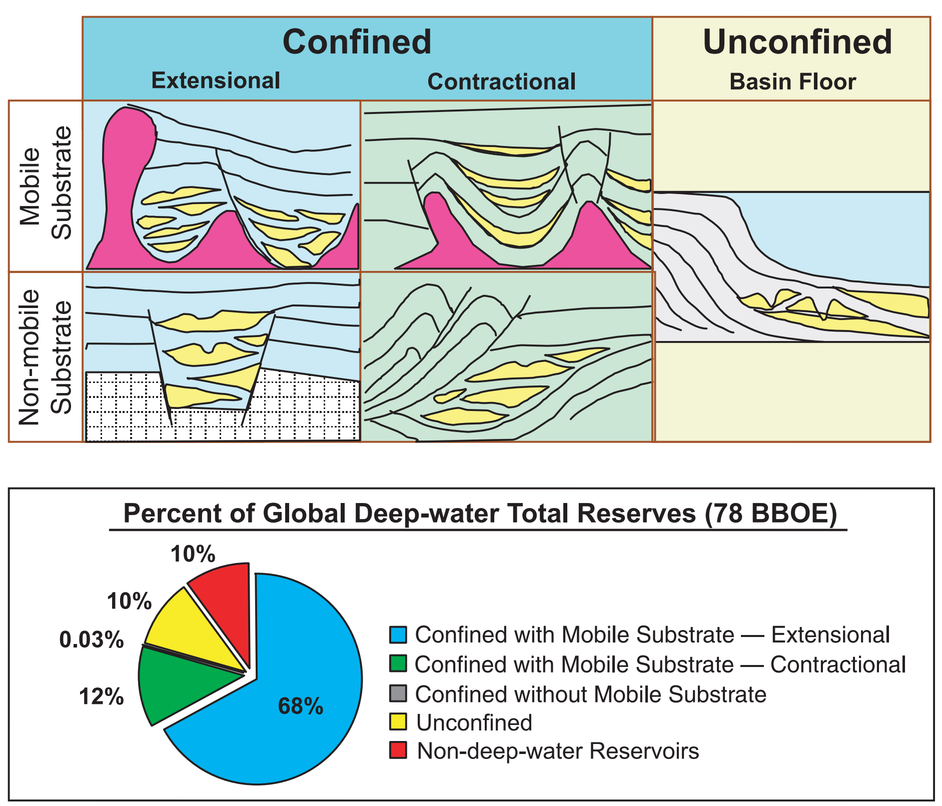




**Figure 5.** Discovered resources versus deep-water basin setting. Classification of mobile substrate and unconfined turbidite settings is adapted from Worrall et al. (1999, 2001). Additional frontier settings are added here, with corresponding reserves from this study. Note that "confined" and "unconfined" are end members, and basins may evolve from one to the other end member or vary spatially between end members. A portion (0.03%) of the confined resources are actually in a low-confinement setting (e.g., Marlim and Albacore Fields, Campos Basin, Brazil), as shown on the chart. After Weimer and Pettingill (2004).

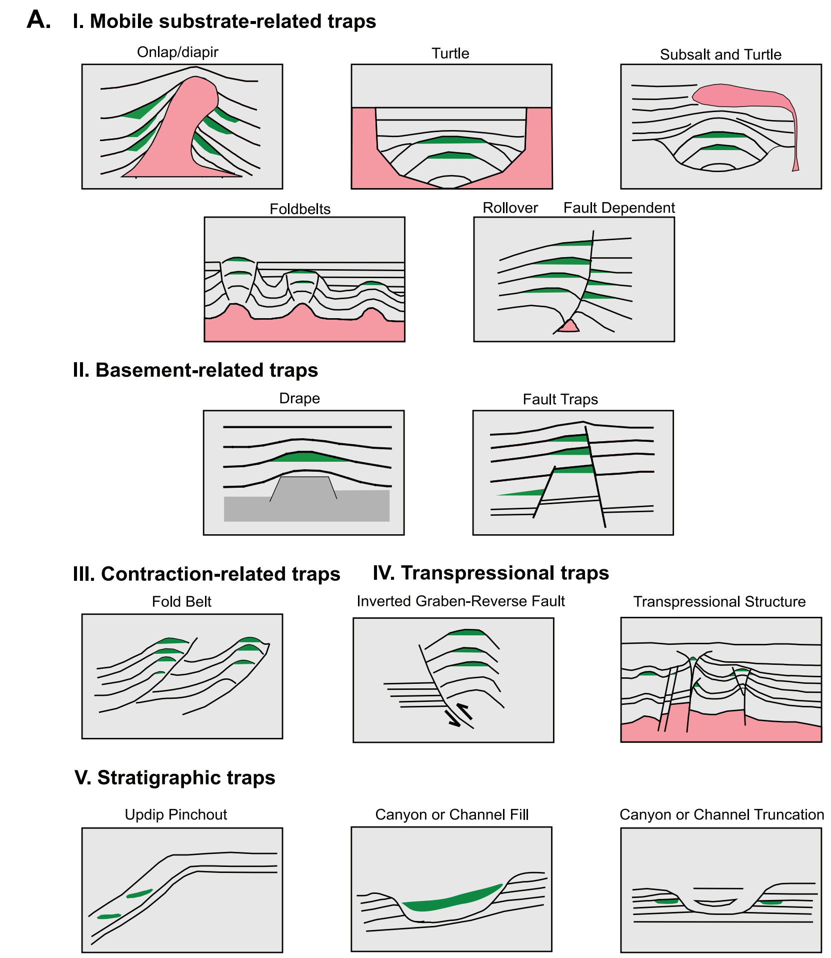
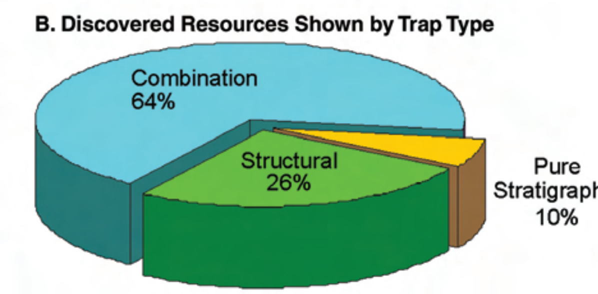
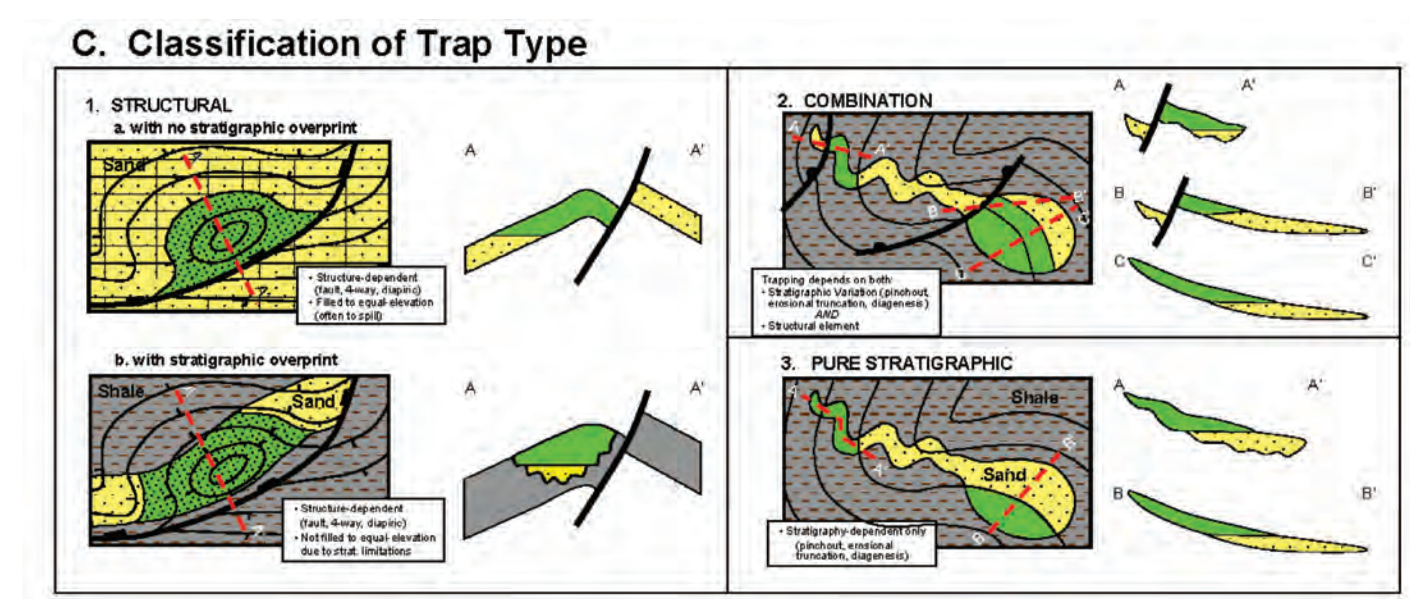



**Figure 6.** A) Schematic diagrams showing different trap styles for the deep-water settings. B) Discovered deep-water resources versus the trap categories. As observations are preliminary, total resources with published trap information are 28 BBOE (about one-third of the resources discovered). C) Classification of trap type employed in this study. As defined by this classification scheme, structural traps have only structural elements (faults, dip-closure, or diapir interface), whereas pure stratigraphic traps depend solely on reservoir discontinuity. Combination traps, however, exist only if both types of elements are in place.



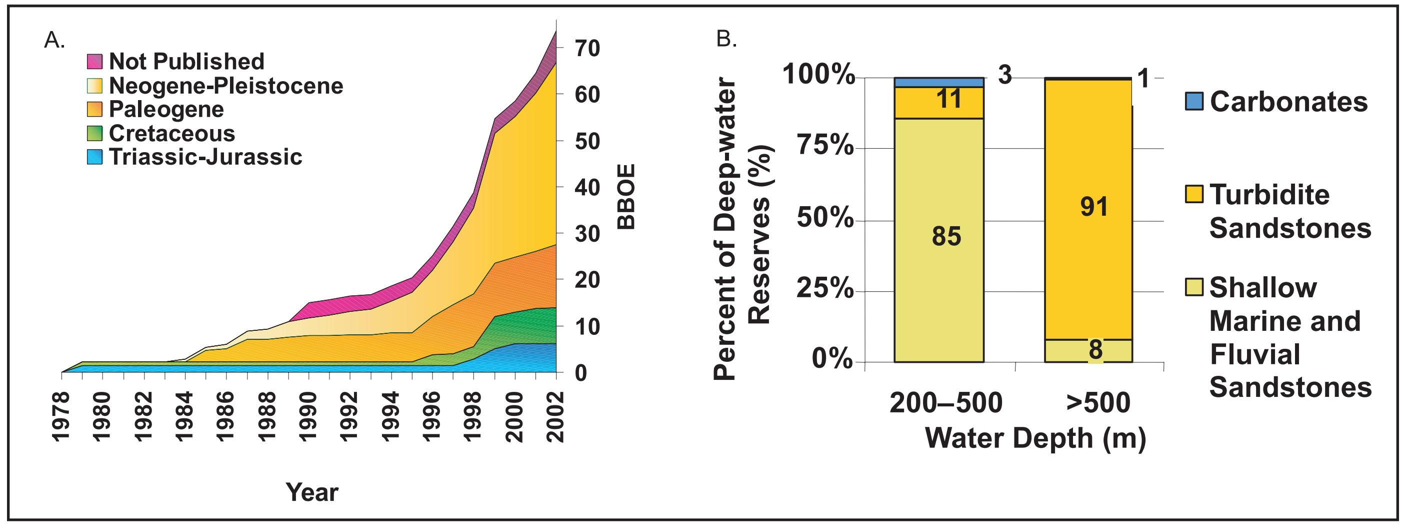



**Figure 7.** A) Deep-water resources discovered from 1978 to 2000 plotted versus reservoir age and B) deep-water resources versus lithology. Lithology data for 200–500 m (655–1640 ft) water depths are from Cook (1999, used with permission); data for >500 m (>1640 ft) are from Pettingill and Weimer (2001). Note the differences in reservoir types with water depths. After Weimer and Pettingill (2004).

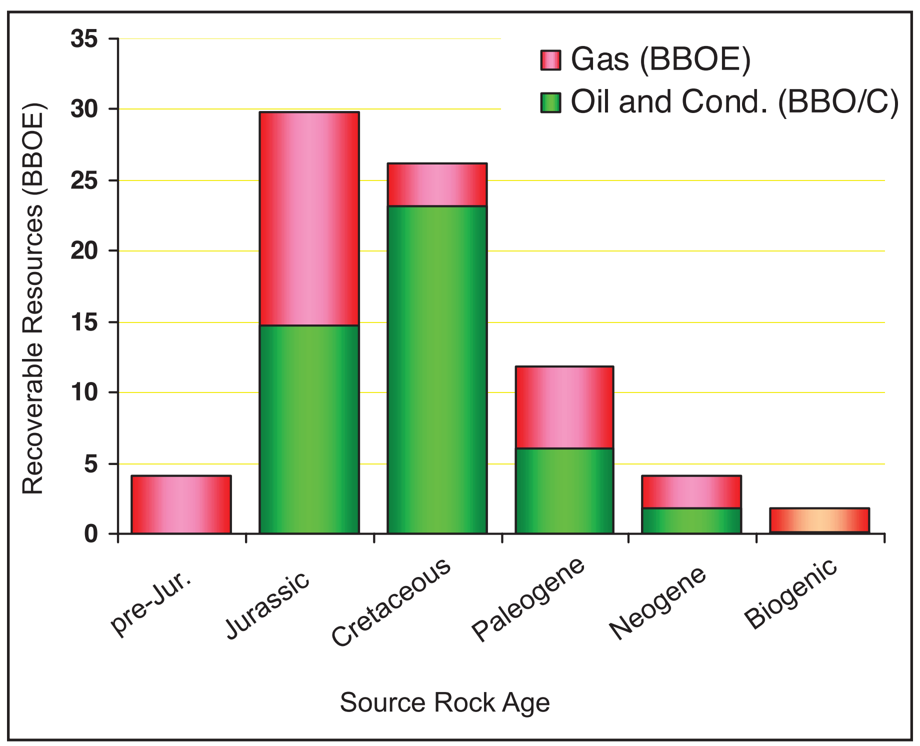



**Figure 8.** Recoverable resources in deep water versus the age of the source rocks. Most of the discovered resources have Jurassic or Cretaceous source rocks. After Pettingill and Weimer (2001).

**Field ultimates, rates, drilling success vs. DHI, and development/exploration methodologies**

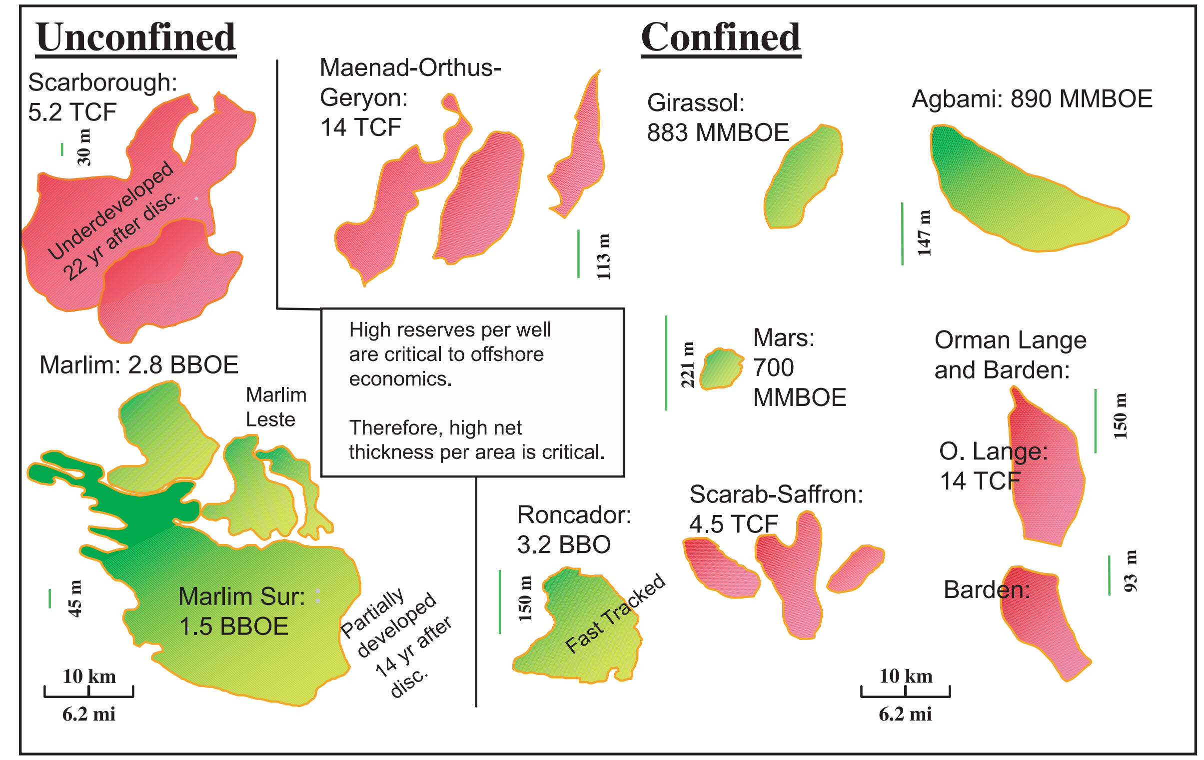



**Figure 9.** Deep-water giant fields with field area and net pay (vertical bar) drawn at identical scales. In general, those reservoirs deposited in confined basins have smaller trap areas and larger net pay values than do reservoirs deposited in unconfined settings. Reservoirs deposited in unconfined settings include Scarborough (northwestern Australia) and the Marlim complex (Campos Basin, offshore Brazil). Reservoirs deposited in confined settings include Maenad-Orthus-Geryon (offshore northwest Australia), Girassol (offshore Angola), Agbami (offshore Nigeria), Mars (northern Gulf of Mexico), Ormen Lange and Barden (offshore Norway), Roncador (Campos Basin, offshore Brazil), and Scarab-Saffron (offshore Nile delta). Modified from Pettingill and Weimer (2001).

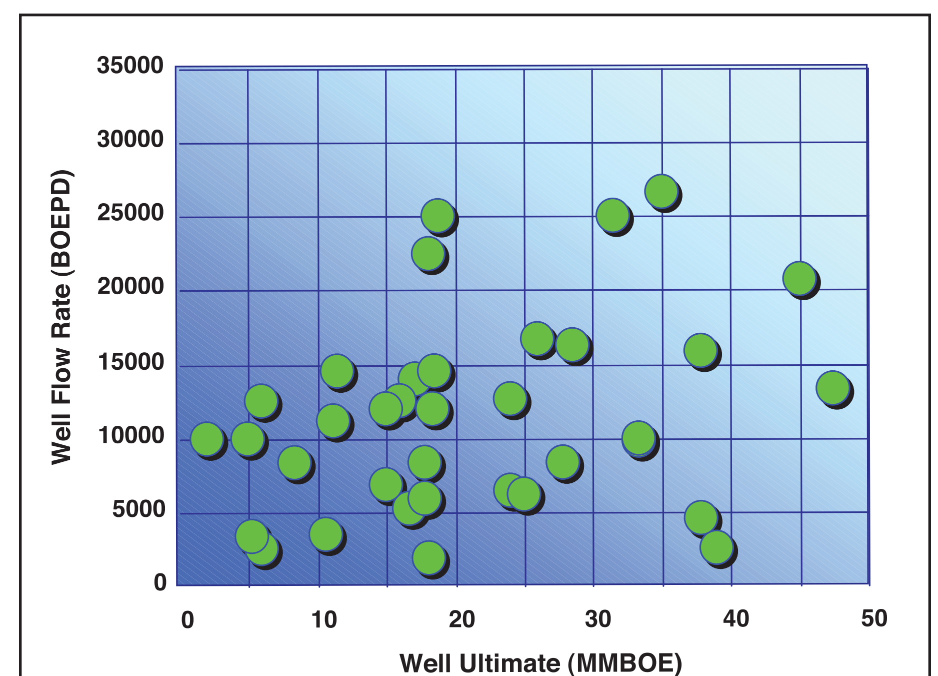



**Figure 10.** Cross-plot of well flow rates versus ultimate production from individual wells. High-rate, high-ultimate (HRHU) reservoirs plot in the upper right part of the graph.

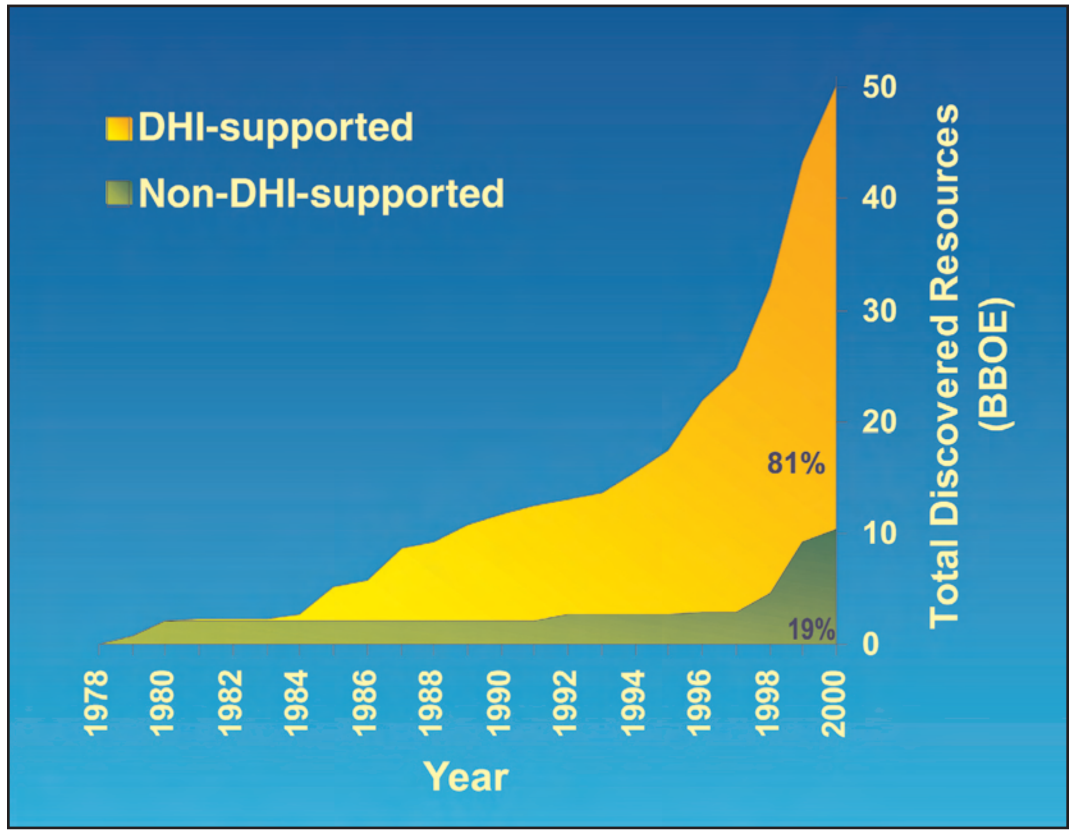



**Figure 11.** Percentage of deep-water reserves with DHI-support versus those lacking DHI-support. After Weimer and Pettingill (2004).

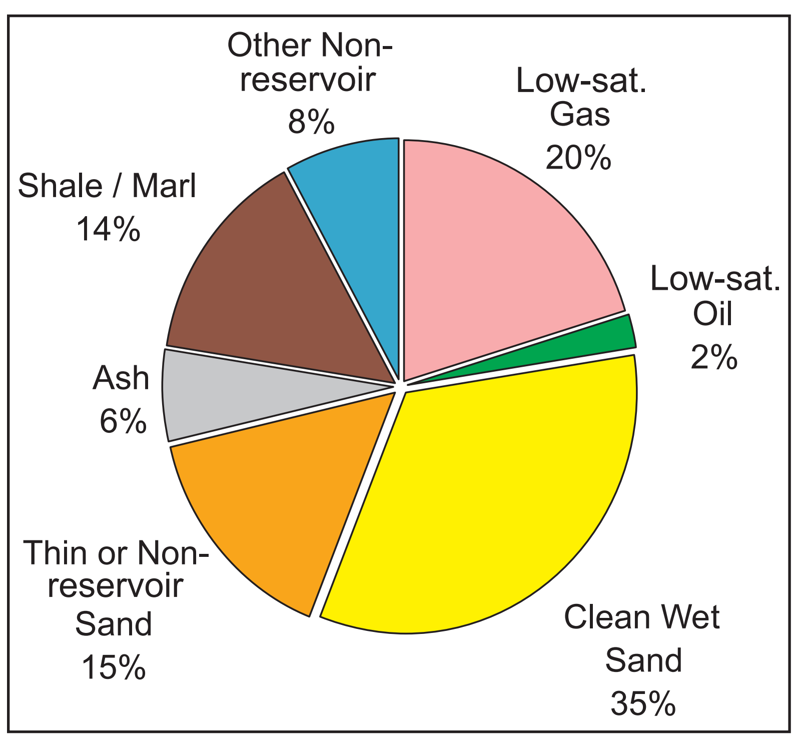



**Figure 12.** Exploration failures using DHI (relative percentages) in exploration for deep-water sands or sandstones. Reprinted with permission of Mike Forrest and Rocky Roden.

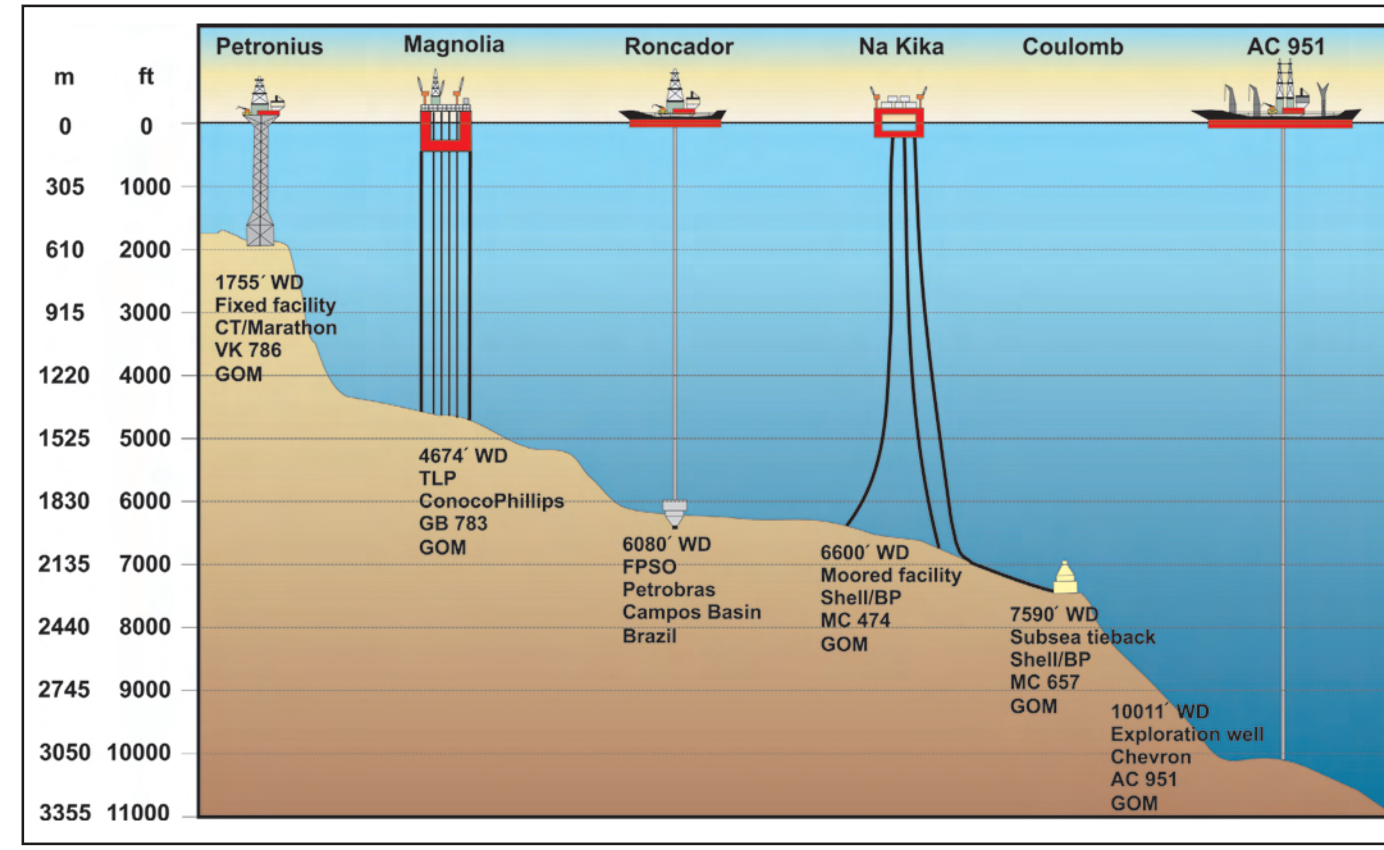



**Figure 13.** Schematic figure illustrates the world-record water depths for exploration and development efforts: fixed facility-Petronius Field, 535 m (1755 ft) Viosca Knoll Block 786, northern Gulf of Mexico; tension leg platform (TLP)-Magnolia Field, 1425 m (4674 ft), Garden Banks Block 783, northern Gulf of Mexico; floating production storage offloading unit (FPSO), Roncador Field, 1854 m (6080 ft), Campos basin, Brazil; moored facility, Na Kika Complex, 2012 m (6600 ft), Mississippi Canyon Block 474, northern Gulf of Mexico; subsea tie-back, Coulomb Field, 2314 m (7590 ft), Mississippi Canyon Block 657, northern Gulf of Mexico; exploration well, 3052 m (10,011 ft), Alaminos Canyon Block 951, northern Gulf of Mexico. Figure is adapted from several sources.

## References


Cook, L., 1999, Deep-water — A global perspective: AAPG International Conference, Extended Abstracts with Program, p. 133.

Harper, F., 1997, Oil and gas beyond the continental shelf: Integrated Coastal Zone Management Exclusive Economic Zone, Edition 1.

Pettingill, H. S., and P. Weimer, 2001, Global deep water exploration: Past, present and future frontiers, *in* R. H. Fillon, N. C. Rosen, P. Weimer, A. Lowrie, H. W. Pettingill, R. L. Phair, H. H. Roberts, and B. Van Hoorn, eds., Petroleum systems of deepwater basins: Global and Gulf and Mexico experience: Gulf Coast Section–SEPM Bob F. Perkins 21st Annual Research Conference, p. 1–22.

Weimer, P., and H. W. Pettingill, 2004, Global overview to deepwater exploration and production, Chapter 2, Petroleum systems of deepwater settings: Society of Exploration Geophysicists/European Association of Geoscientists & Engineers Distinguished Instructor Short Course Lecture notes, p. 2-1–2-39.

Worrall, D. M., B. E. Prather, and J. Straccia, 1999, Frontier deep-water basins: What's next?: AAPG International Conference and Exhibition, Extended Abstracts with Program, p. 514.

Worrall, D. M., M. W. Bourque, and D. R. Steele, 2001, Exploration in deep water basins . . . where next? *in* R. H. Fillon, N. C. Rosen, P. Weimer, A. Lowrie, H. W. Pettingill, R. L. Phair, H. H. Roberts, and B. Van Hoorn, eds., Petroleum systems of deepwater basins: Global and Gulf and Mexico experience: Gulf Coast Section–SEPM Bob F. Perkins 21st Annual Research Conference, p. 273.